On the global triggering mechanism of star formation in galaxies.

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ABSTRACT

We study the large-scale triggering of star formation in galaxies. We find that the largest mass-scale not stabilized by rotation, a well defined quantity in a rotating system and with clear dynamical meaning, strongly correlates with the star formation rate in a wide range of galaxies. We find that this relation can be explained in terms of the threshold for stability and the amount of turbulence allowed to sustain the system in equilibrium. Using this relation we also derived the observed correlation between the star formation rate and the luminosity of the brightest young stellar cluster

Subject headings: galaxies: disk instabilities - galaxies: formation - star formation: general

1. Introduction

Observations of normal spiral galaxies by Schmidt (1959) first suggested that their star formation rates (SFR) scales with the global properties. This conclusion was extended to other galaxies with higher SFR, such as the nuclear regions of spiral galaxies and Ultra Luminous InfraRed Galaxies (ULIRGs) by Kennicutt (1998). These galactic scale observations have lead to an empirical law for star formation called Kennicutt-Schmidt (KS) Law:

$$\dot{\Sigma}_{\rm star} \propto \Sigma_{\rm gas}^{1.4} \ , \tag{1}$$

where $\Sigma_{\rm gas}$ and $\dot{\Sigma}_{\rm star}$ are the gas surface density and SFR per unit area.

Since star formation is a local process that happens on subparsec scale, the correlation with global (galactic scale) quantities such as averaged $\Sigma_{\rm gas}$, suggest the existence of a physical connection between galactic ($>$ 1 kpc) and subparsec scales. Motivated by the existence of the KS law, several authors have tried to find the link in which a global/large

scale property of galaxies could trigger and/or regulate star formation in them (Quirk 1972; Wyse 1986; Larson 1987; Kennicutt 1989; Silk 1997; Tan 2000; Elmegreen 2002; Li et al. 2005). It is also important to note that the KS law can still be explained in terms of mainly local processes within starforming clouds (Krumholtz et al. 2009 and references therein).

From the study of gravitational instabilities in disks, the Toomre parameter $Q \equiv C_s\kappa/\pi G\Sigma$ (or variations of that such as the star formation threshold $\Sigma_{\rm crit}$; Kennicutt 1989) arises as the most natural candidate as key triggering parameter. However, the average Q in a galaxy is observed to be never too far from 1, from local spiral galaxies (Martin & Kennicutt 2001), to starbursts such as ULIRGs (Downes & Solomon 1998). This is believed to be due to self-regulating feedback processes in the following way (Goldreich & Lynden Bell 1965): if $Q >> 1$, then the disk will cool rapidly and form stars, while if $Q << 1$, then the star formation will be so efficient that the disk will heat up to $Q \sim 1$. Observed variations of Q (or $\Sigma_{\rm gas}/\Sigma_{\rm crit}$) are at best within factors of a few, which makes hard to explain the variations of 6-7 orders of magnitude that varies the SFR in galaxies, solely in terms of this threshold.

However, for different disks all at the condition of marginal Toomre stability, is still possible to have different equilibrium states and this is the topic that we will explore in this *Letter*. The aim of this work, is to study why the SFR in some galaxies can be orders of magnitude higher than in other ones, more specifically, which galactic property triggers this behavior.

This work is organized as follows. Starts with a review the gravitational instability analysis with a focus on the role of turbulence in §2. In §3, continues studying the effects of the global threshold for stability on the star formation activity, and the implications of this. Finally in §4, we discuss the results of this *Letter*.

2. GRAVITATIONAL INSTABILITY IN REAL ISM AND THE ROLE OF TURBULENCE

We start reviewing some standard results from gravitational instability analysis (Toomre 1964; Goldreich & Lynden Bell 1965). For one of the simplest cases of a differentially rotating thin sheet or disk, linear stability analysis of such a system yields the dispersion relation for small perturbations (Binney & Tremaine 2008) of $\omega^2 = \kappa^2 - 2\pi G\Sigma|k| + k^2 C_{\rm s}^2$. Where $C_{\rm s} = \sqrt{\frac{dP}{d\Sigma}}$ is the sound speed, Σ is the surface density, and κ is the epicyclic frequency , which is given by $\kappa^2(R) = R\frac{d\Omega^2}{dR} + 4\Omega^2$ (being Ω the angular frequency). The system becomes unstable when $\omega^2 < 0$ which is equivalent to the condition $Q < 1$, where Q is the Toomre

parameter and is defined as $C_s\kappa/\pi G\Sigma$. In such a case, there is a range of unstable length scales limited on small scales by thermal pressure (at the Jeans length $\lambda_{\rm Jeans} = C_s^2/G\Sigma$) and on large scales by rotation (at the critical length set by rotation, $\lambda_{\rm rot} = 4\pi^2 G\Sigma/\kappa^2$). All intermediate length scales are unstable, and the most rapidly growing mode has a wavelength $2\,\lambda_{\rm Jeans}$.

The maximum unstable length scale in a disk, $\lambda_{\rm rot}$, is a robust quantity because it depends only on the surface density and epicyclic frequency of the disk and not on the smaller scale physics. Such scale has a characteristic mass associated, defined equals to $\Sigma_{gas}(\lambda_{\rm rot}/2)^2$ and that can be expressed as:

$$\mathrm{M_{rot}} = \frac{4\pi^4 \mathrm{G}^2 \Sigma_{\rm gas}^3}{\kappa^4}\,. \tag{2}$$

Contrarily, due to the complex structure and dynamics of real interstellar medium (ISM) in galaxies, which cannot be described by a simple equation of state, there is not a well-defined Jeans length at intermediate scales. Therefore, no real lower limit on the sizes of the self-gravitating structures that can form until the thermal Jeans scale is reached in molecular cloud cores (Escala & Larson 2008).

One of the intermediate scales usually claimed to be a relevant in the stability of the ISM, is the Jeans length defined by the turbulent pressure in the medium ($\lambda_J^{turb} = v_{\rm turb}^2/G\Sigma$). Besides the convenience of the idea of a turbulent pressure term that generalize the gravitational instability analysis, this term is however not a well defined quantity in ISM (Elmegreen & Scalo 2004). This comes from the fact that this pressure term could only be defined in the case where the dominant turbulent scale is much smaller than the region under consideration (‘microturbulence’), which is in fact is not the case of ISM. Rigorous analysis endeed shows that turbulence can be represented as a pressure only in the microturbulence case (Bonazzola et al. 1992). Besides turbulent motions could help to prevent collapse on some scales, those complex motions cannot be represented as a pressure. Therefore the gravitational instability analysis is not strictly applicable with a turbulent pressure term that could stabilize and damp all the substructure below λ_J^{turb}.

Although turbulence cannot be modelled as simple pressure supporting term that will prevent all gravitational instabilities below some scale, turbulence could prevent the growth of instabilities by heating the gas trough compression. However, compression from turbulence not only heat the gas, but also may enhance collapse and star formation on smaller scales (Elmegreen 2002; Krumholtz & Mckee 2005). Only when the turbulent heating becomes faster than the gas cooling, the net effect of turbulence is to effectively heat the gas and therefore prevent gravitational instabilities. Once this condition is satisfied the gas is heated

towards $c_S \sim v_{turb}$, the thermal pressure will stabilize and damp all the substructure below $\lambda_J \sim \lambda_J^{turb}$. If the condition $\lambda_J \sim \lambda_{rot}$ (equivalent to $Q \sim 1$) is also satisfied, the system will then became globally stable.

A well studied case in which both conditions could be satisfied, is in self-gravitating protoplanetary disks where the heating is due to gravito-driven turbulence. Gammie (2001) showed that turbulence heat the gas such the system becomes stable on all scales ($Q > 1$), when $t_{cool} > 3\,t_{dyn}$, being t_{cool} and t_{dyn} the cooling and orbital times. Such disk is in an equilibrium state (so-called '*gravitoturbulence*') that experiences significant fluctuations, but the disk is stable against fragmentation and maintains itself in the brink of instability (Rafikov 2009)

Galaxies are indeed observed to be close to equilibrium (Martin & Kennicutt 2001; Downes & Solomon 1998), with observed Toomre Q parameters never too far from 1 (averaged over the whole system and using the turbulent version of the Toomre parameter; $Q_{turb} = v_{turb}\kappa/\pi G\Sigma$). This is due to self-regulation heating/cooling processes: if $Q_{turb} >> 1$, in the absence of heating driven by instabilities the disk will cool rapidly and the system will eventually become unstable, while if $Q_{turb} << 1$, then the self-gravity and star formation feedback will be so efficient that will produce enough turbulence to heat the disk towards $Q_{turb} \sim 1$.

However, galaxies are in an state that departs somewhat from the '*gravitoturbulent*' one found by Gammie (2001). Because in galaxies only the turbulent Q Toomre parameter is close to one, not the thermal Q which is the one that guarantees stability (like in '*gravitoturbulent*' state). Galaxies are only close to stability, the runaway growth of density fluctuations is not suppressed and the formation of bound objects on different scales is ongoing (i.e. star formation, GMC formation, etc). They are probably oscillating around marginal stability due to the self-regulation feedback process, in a more dynamical fashion (and with larger oscillations) than the one studied in Gammie (2001).

Besides this more complex behavior of ISM in galaxies compared with the classical self-regulated '*gravitoturbulent*' state studied in protoplanetary disks, the threshold is still well defined and there is self-regulation processes toward this marginal state. The marginal stability is well defined at thermal Q=1 and this happens when the following two conditions are satisfied: $Q_{turb} \sim 1$ and $t_{cool} > t_{heat}$.

3. Global Threshold for Stability and its Effect on the Star Formation Activity

Besides most disks in galaxies are in the same state of being close to marginal Toomre stability, still some disks like nuclear disks in starbursts are able to be much more turbulent than others such as the disks of spiral galaxies. The reason is that is still possible to have different equilibrium solutions for $Q \sim 1$, which is equivalent to $M_{rot} \sim M_{Jeans}$. Simply because some disks starts with a higher threshold for stability (a larger mass-scale not stabilized by rotation, M_{rot}), their large-scale conditions requires to the self-regulation processes to produce more turbulence in order to heat the gas towards this higher value for globally stabilize the system. Under this view, the self-regulation drives the system towards an equilibrium with a higher level of turbulence, and this more turbulent state is triggered by the initial condition of having a system with higher threshold for stability.

The existence of different equilibriums in disks is particularly relevant because is believed that turbulence has a role in enhancing and possibly controlling star formation (Elmegreen 2002; Krumholz & McKee 2005; Wada & Norman 2007). On its simplest form (proposed by Elmegreen 2002) the SFR depends on the probability distribution function (PDF) of the gas density produced by galactic turbulence, which appears to be lognormal in simulations of turbulent molecular clouds and interstellar medium (Wada & Norman 2001; Ballesteros-Paredes & Mac Low 2002; Padoan & Nordlund 2002; Li et al. 2003; Kravtsov 2003; Mac Low et al. 2005; Wada & Norman 2007; Wang & Abel 2009). The dispersion of the lognormal PDF, is believed to be determined by the rms Mach number of the turbulent motions if high-density regions are formed mainly through shock compression in a system (Vázquez-Semadeni 1994; Padoan et al. 1997; Nordlund & Padoan 1998; Scalo et al. 1998). Therefore it is expected that the SFR in galaxies scales with the velocity dispersion of turbulent motions.

In summary, the existence of a higher threshold for stability (M_{rot}) and the self-regulation towards marginal stability, allows the disk to be in equilibrium with a higher turbulence level, which itself enhances a higher star formation activity. Therefore, both galactic-scale processes (M_{rot}) and local processes (turbulence within molecular clouds) are relevant in regulating star formation. This global well-defined scale in disks, M_{rot}, plays the role of triggering turbulence and therefore the star formation activity in galaxies.

In order to test if this scenario is correct, we will check if the mass-scale defined by rotation (Eq. 1) correlates with the star formation rate as expected. For a rotationally supported system, the average of this mass-scale can be expressed in terms of quantities such as the total gas mass and gas fraction, that are easier to compare with observations

(Escala & Larson 2008):

$$\mathrm{M_{rot}} = 3\ 10^7\,\mathrm{M_\odot}\ \frac{\mathrm{M_{gas}}}{10^9\,\mathrm{M_\odot}} \left(\frac{\eta}{0.2}\right)^2, \tag{3}$$

where $\mathrm{M_{gas}}$ is the total gas mass in the disk and $\eta = \mathrm{M_{gas}}/\mathrm{M_{dyn}}$ is the ratio of the gas mass to the total enclosed dynamical mass within the gas radius (this varies from the disk radius for spiral galaxies, to the radius of the nuclear starburst disk/ring in ULIRGs).

In figure 1a we plot the stability threshold defined by rotation estimated from Eq. 3, against the measured star formation rate in those galaxies. With stars we plot the data taken for normal spirals (Kennicutt 1998; Kent 1987; Pisano et al. 1998; Giraud 1998; Theis 2001; Braine 2001; Leitherer 2002; Helfer et al. 2003; Gallagher 2005; Afanasiev 2005; Davidge 2006; Pérez-Torres & Alberdi 2007; Thilker et al. 2007), with open circles for the nuclear gas in normal spirals (Jogee 2005; Mauersberger et al 1996; Alonso-Herrero 2001; Hsieh et al 2008) and with full circles for ULIRGs (Downes & Solomon 1998). Figure 1a shows a clear correlation between $\mathrm{M_{rot}}$ and the star formation rate, in agreement with the scenario outlined in this *Letter*. Figure 1a supports the critical role of this threshold mass in the triggering of star formation. The solid line in figure 1a represents a star formation law of $\mathrm{SFR} \propto \mathrm{M_{rot}^{1.4}}$.

For comparison purposes we also plot in figure 1b the measured star formation rate against the square of the gas fraction η. Figure 1b clearly shows that the scatter in this relation is considerably increased compared to figure 1a. This means that the gas fraction is not a more fundamental parameter in controlling the star formation rate. We do not plot the SFR against the gas mass, since it is well established that there is no correlation of the total gaseous mass in galaxies with their current star formation rate.

In summary, the predicted correlation between the SFR and the maximum unstable mass defined by rotation is indeed observed in galaxies, in a range that spans for 5 orders of magnitude in SFR. This is an strong suggestion that the global threshold for instability indeed triggers star formation, by allowing the disk to be in equilibrium configuration with a higher turbulence level.

3.1. Relation between the SFR and most luminous young stellar cluster

Probably the most straightforward application of the scenario outlined in §2, is to check if its able to explain the observed correlation between the star formation rate of a galaxy and the luminosity of its brightest young stellar cluster (Larsen 2002; Bastian 2008). This is because the mass-scale studied here and that correlates with the SFR (Fig 1), also corresponds to the most massive unstable cloud in a disk, which could lead to the formation of

the most massive and luminous young cluster in such system (Escala & Larson 2008).

The total luminosity of a cluster, can be computed for a given initial mass function (IMF) and mass-luminosity relation. Assuming a Salpeter IMF ($\frac{\mathrm{dN}}{\mathrm{dm}} \propto \mathrm{m}^{-2.35}$) and the usual mass-luminosity relation for main sequence stars ($\mathrm{L} \propto \mathrm{m}^{3.5}$), the total luminosity of a cluster is given by

$$\mathrm{L_{tot}} \propto \mathrm{M_{cloud}^{0.92}}\,, \tag{4}$$

where $\mathrm{M_{cloud}}$ is the total mass of the parent cloud that formed the cluster, which is assumed to satisfy the observed relation with the most massive star of such cluster: $\mathrm{M_{star}^{max}} \sim \mathrm{M_{cloud}^{0.43}}$ (Larson 1982).

Taking into account the correlation found between the most massive unstable cloud and the star formation rate in galaxies (Fig 1), which is approximately $\mathrm{M_{cloud}^{max}} \propto \mathrm{SFR}^{\frac{1}{1.4}}$, the total luminosity of the brightest cluster is given by $\mathrm{L_{tot}^{brightest}} \propto \mathrm{SFR}^{0.66}$. Finally, this can be expressed in terms of absolute magnitude in the V-band by $\mathrm{M_V^{brightest}} = 4.79 - 2.5\,\mathrm{Log L_V^{brightest}}$, arising to the relation:

$$\mathrm{M_V^{brightest}} \propto -1.65\ \mathrm{Log\,SFR}\,, \tag{5}$$

which is in good agreement with the observed slope of -1.87 (Weidner et al. 2004). Particularly good if we take into account all the uncertainties in the assumptions, such as the slopes of the IMF and the mass-luminosity relation.

4. SUMMARY

In this Letter we have studied gravitational instabilities in disks, with special attention on the role of turbulence in stabilizing the system. We discussed that although turbulent motions cannot be modelled as a pressure supporting term, turbulence can still make a disk globally stable when both the turbulent Toomre ($\mathrm{Q_{turb}} > 1$) and Gammie ($\mathrm{t_{cool}} > \mathrm{t_{heat}}$) conditions are satisfied. This allows to the global threshold for stability, which is defined by largest scale in galactic disks not stabilized by rotation, to have a clear role in the dynamics of the ISM.

For a disk with a larger scale not stabilized by rotation, its dynamical equilibrium configuration ($\mathrm{Q} \sim 1$) is with a more turbulent ISM. Therefore, the role of the global threshold for stability in a disk is to define up to which amount the generation of turbulence is allowed. Since turbulence enhance collapse on small scales and therefore star formation, on the scenario proposed in this Letter, we expect a correlation between the mass-scale for global stability and the star formation rate.

We found that this relation is indeed observed in galaxies that ranges from ULIRGs to normal spirals. Compared with other relations such us Kennicutt-Schmidt Law, its relevance rely on that is the only correlation of the star formation rate with a quantity with clear dynamical meaning on galactic scales.

We also explore the implications of this predicted relation between global stability and the star formation rate. We found that based on this relation, we are able to explain the observed correlation between the star formation rate in galaxies and the most luminous young stellar in them.

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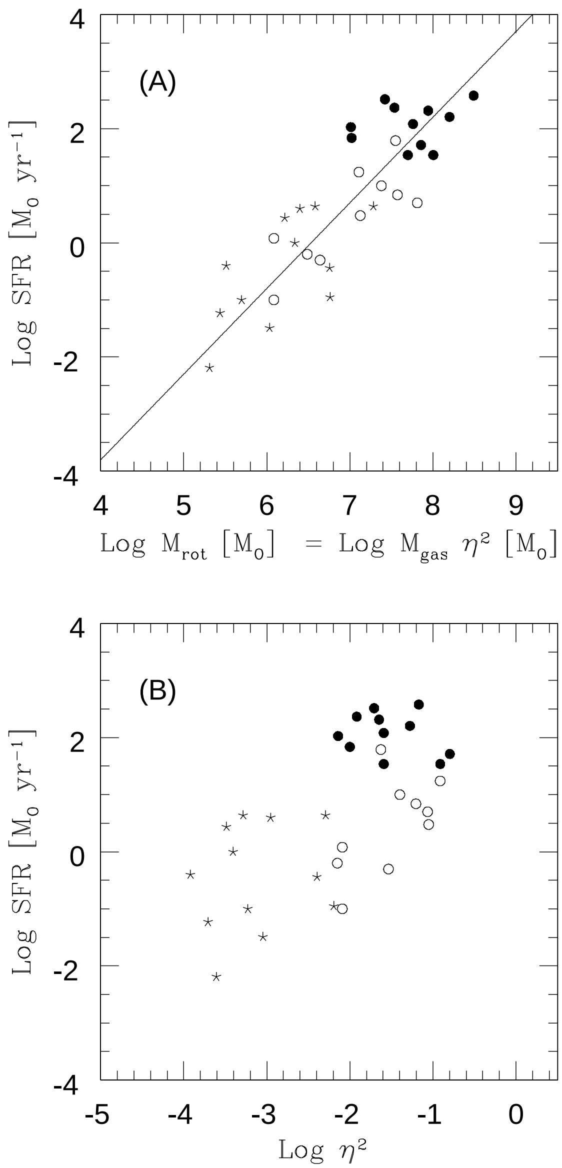

Fig. 1.— a) The star formation rate plotted against the critical mass-scale defined by rotation M_{rot}, estimated from Eq. 3 using measured quantities in those galaxies. The black dots shows data for nuclear starburst disks, the stars for normal spirals galaxies and the open circles for nuclear gas in spirals. The solid line corresponds to SFR $\propto M_{rot}^{1.4}$. b) The star formation rate plotted against the square of the gas fraction $\eta = M_{gas}/M_{dyn}$, using the same symbol nomenclature as in a).